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Induction Bonding for Structural Composite Tubes

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Abstract

Large structural composite tubes, prototype components for a proposed U.S. Navy application, are bonded by induction curing of an engineering adhesive. Magnetic powder is used as the susceptor material and is directly incorporated into the adhesive prior to processing. Different induction power supplies, coil designs, and adhesive formulations are investigated. Final demonstration runs bond 9-in-long, 3-in-diameter axisymmetric bondlines in 15 min. These results demonstrate for the first time the successful induction bonding of large structural composite components using magnetic particulate susceptors.

Acknowledgments

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1. Introduction

1.1 Application

The U.S. Navy has identified the need for long, flexible, lightweight tubes for a future sea-based application. The expected tube lengths are tens to hundreds of feet and will need to be able to support moderate loads.

Glass fiber-reinforced polyurethane composites have been identified as a potential material solution. Polymer matrix composites are, in general, lightweight and not susceptible to corrosion in salt water environments. Polyurethane composites offer low stiffness and high strains to failure, with wide tailorability of mechanical properties through composite architecture.

The most efficient fabrication method for long axisymmetric composite components is filament winding. However, the length of the proposed tubes is well beyond the capabilities of conventional filament-winding equipment. An alternative approach is to filament-wind short sections and then adhesively bond these sections to form the longer tube.

The structural strengths required for this application necessitate the use of engineering adhesives. Most of these adhesive systems require elevated temperature cures, which are typically achieved using convection ovens or infrared heaters. However, these surface heating approaches can be very slow, since they rely on through-thickness thermal conduction to transfer heat from the part surface to the bondline. This problem is especially severe in low thermal conductivity materials such as glass fiber composites. The large size of the bonded tubes also presents tooling difficulties, since they are too large to fit in conventional convection ovens.

1.2 Induction Bonding

1.2.1 Magnetic Particles and Adhesive Bonding

An alternative heating approach is to use induction curing of adhesives (Wetzel and Fink 2001). An induction field is a high frequency electromagnetic field, typically operating at frequencies from 0.1 to 100 MHz. Most materials, including glass composites and conventional adhesives, do not interact with induction fields. However, "susceptor materials," such as metals and magnetic materials, heat in the presence of an induction field.

This behavior can be exploited by mixing magnetic fillers into conventional adhesives. In the presence of an induction field, the doped adhesive will heat inductively and cure. This approach is superior to conventional surface heating

methods because the bondline is heated directly. By selectively heating only the bondline, overall process times and energy requirements are reduced.

Magnetic particles heat in an induction field due to magnetic hysteresis mechanisms. The alternating magnetic field causes the material to magnetize and demagnetize cyclically, a process which is not thermodynamically reversible. The losses associated with this magnetization process are liberated in the form of heat. In general, the rate of heat generation is directly proportional to frequency, so that it is advantageous to use higher frequency induction fields. Heating also generally increases with magnetic field amplitude up to some limiting saturation strength. The details of the mechanisms of induction heating of magnetic materials can be found in Wetzel and Fink (2001).

The saturation magnetization of magnetic materials usually decreases with temperature. In very pure materials, the magnetic properties will drop precipitously at a characteristic temperature called the Curie temperature. The decrease in magnetic properties with temperature, in most cases, also causes a drop in the magnitude of heat generation in an induction field. This behavior limits the temperature to which a magnetic material can be self-heated. In fact, it has been shown that the dwell temperature of very pure materials in an induction field is closely related to the Curie temperature (Wetzel et al. 2000). These inherent temperature limits enable rapid heating while minimizing the risk of exceeding critical upper process temperatures.

1.2.2 Generation of Induction Fields

Induction fields are generated using a high frequency power supply connected to an induction coil. The induction coil is typically a winding of copper tubing, through which cooling water is circulated. The power supply sends a high frequency current through the copper tubing, which then generates a high frequency magnetic field in the vicinity of the coil.

Coil geometry design can be used to control the distribution of magnetic fields produced. In general, magnetic field strength is highest near the coil. Therefore coils are designed such that their windings are close to the area to be heated. Larger coils allow the production of magnetic fields over larger areas, enabling heating of larger parts. However, these large coils usually also have large inductances. Since most induction heaters operate under resonant conditions, there is only a limited range of coil inductances which can be tolerated. These tuning considerations limit induction coil size.

1.3 Objective

The objective of this report is to demonstrate the feasibility of induction processing for adhesively bonding large composite tubes for a U.S. Navy application. Curing structural adhesives using induction fields has been demonstrated before, typically using embedded metallic susceptors (McKnight et

al. 1998; Yarlagadda et al. 2000; Tay et al. 1999; Wedgewood and Hardy 1996) or heating a metallic substrate (Eagle 1987; Stefanides 1987). A few researchers have investigated the use of magnetic particle susceptors for adhesive curing (Fink et al. 1998; Hahn et al. 1991), and patents exist on the technology (Guiles et al. 2000; Clark et al. 1995). This report is the first to demonstrate rapid structural bonding of large components using magnetic particle susceptors.

The research in this report was performed in two phases. Phase I was performed at the University of Delaware Center for Composite Materials (Newark, DE) using a Lepel Corp. (Edgewood, NY) induction power supply. This power supply, which is relatively crude in design, has limited frequency and amplitude capability. Phase II was performed at the U.S. Army Research Laboratory (ARL) (Aberdeen Proving Ground, MD) using an Ameritherm Inc. (Scottsville, NY) power supply. The Ameritherm unit is the current state of the art in commercial high frequency, auto-tuning induction processing equipment.

During each of the two phases, preliminary experiments are performed to properly configure the induction equipment, determine optimal adhesive/filler loading ratios, and select appropriate processing protocols. These preliminary experiments are followed by bonding of large demonstration tubes, which are representative of possible application designs. These prototype tubes will also be mechanically tested at the Naval Undersea Warfare Center (Newport, RI) at a later date.

2. Materials

2.1 Composite Tube Material and Geometry

The composite tubes are filament-wound glass-fiber-reinforced polyurethane. The resin system is Uniroyal Chemical Co. (Middlebury, CT) Adiprene L-100, cured using Uniroyal Caytur 21 curing agent (toluene diisocyanate). Adiprene composites have a relatively low elastic modulus and high strain to failure, allowing the fabrication of highly flexible composite materials. Figure 1 shows the tube geometries. Each of the two tubes is ~9 ft in length with a diameter of roughly 3 in and a wall thickness of 0.28 in. The tubes are bonded along a 9-in-long, tapered, male-female joint. A wind angle of 35° was used for the phase I experiments, while a wind angle of 25° was used for the phase II experiments.

For some of the preliminary bonding experiments, "minitubes" were bonded to simulate the final bonding runs. These minitubes are ~2 ft in length with a diameter of roughly 3 in and a wall thickness of 0.25 in. The tubes are bonded along a 6-in-long, untapered, male-female joint. All minitubes were filament wound at wind angles comparable to the final tubes.

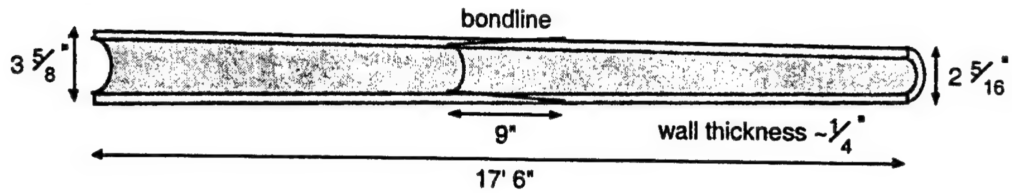


Figure 1. Geometry of full prototype tubes to be bonded.

Conventional adhesives, which are relatively stiff compared to Adiprene, were considered unsuitable for bonding the tubes. The stiffness mismatch could cause unwanted bondline stresses at high bending strains, or limit the flexibility of the bondline areas. Instead, Adiprene L-100 resin, cured using Caytur 21, was used as the adhesive. Although this material is not designed as an adhesive, it was found to produce adequate bond strengths for this application. The recommended cure cycle for Adiprene L-100 with Caytur 21 is 1 hr at 120 °C. This resin system will also gel at room temperature over ~24 hr, although the mechanical properties will be inferior to the elevated temperature cured material.

2.2 Magnetic Materials and Other Adhesive Additives

Nickel-zinc ferrites manufactured by PowderTech (Valparaiso, IN) were used as the magnetic susceptor material. Three particular grades, FP95, FP110, and FP160, were used in this study. These materials are soft ferrites with relatively low Curie temperatures (<200 °C). Figure 2 shows saturation magnetization vs. temperature for these materials, measured using a Lakeshore Cryotronics, Inc. (Westerville, OH) 7300 vibrating sample magnetometer. The saturation magnetizations do not exhibit a sharp drop at a characteristic temperature, as would be expected to occur for a pure material at its Curie temperature. Instead, the gradual decrease in magnetization with temperature indicates that these are probably multiphase materials. This behavior also implies that, in an induction field, these materials will not show obvious self-regulating dwells at their Curie temperature. Instead, they are more likely to reach an ultimate temperature which is highly dependent on the applied field strength and heat transfer conditions.

In all cases, the as-received magnetic particles were dry ball milled for 1–3 hr prior to testing, using a 50 mL tungsten carbide vial and balls. Fifty grams of particles (~10 mL) were milled each cycle, resulting in an average particle size of ~10–100 μm. The magnetic material has a density of ~4.5 g/cm^3. When mixed with the adhesive (with a density of ~1 g/cm^3), a particle weight fraction of 33% roughly corresponds to a volume fraction of 10%, and a particle weight fraction of 50% roughly corresponds to a volume fraction of 20%.

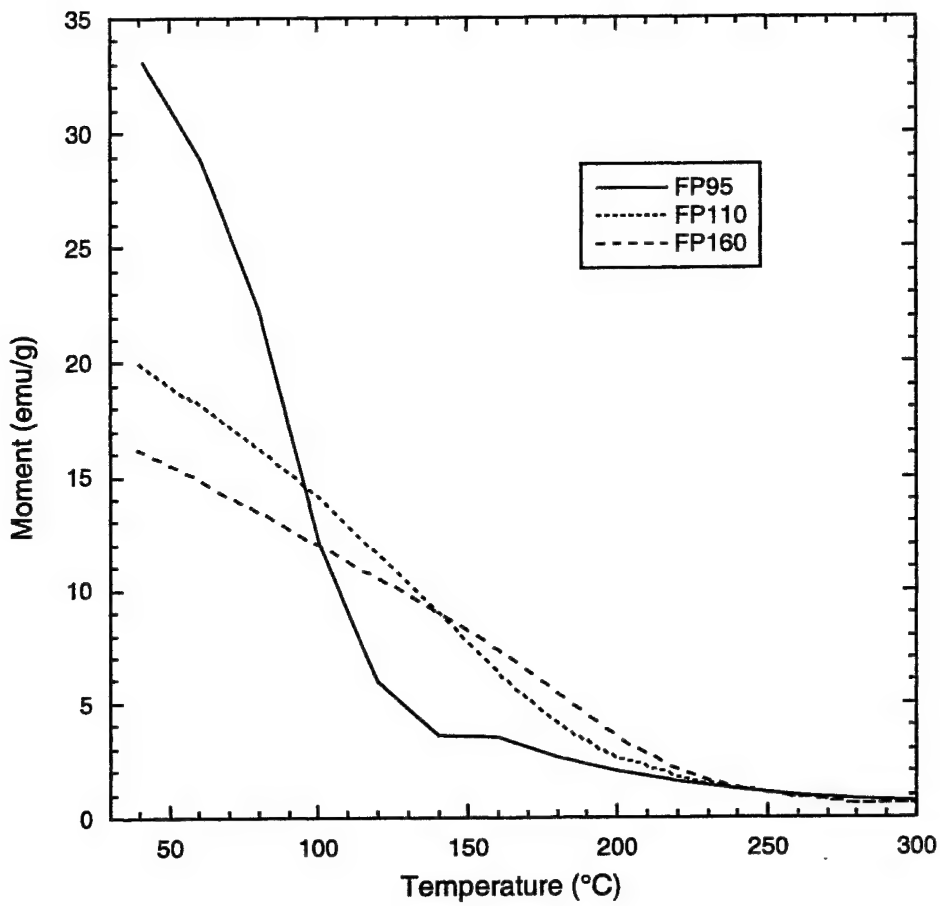


Figure 2. Saturation magnetization as a function of temperature for FP95, FP110, and FP160 powders.

Hollow glass microspheres (Recyclospheres, manufactured by Sphere Services Inc., Oak Ridge, TN) were incorporated into some adhesive formulations to help control bondline thickness. Because these particles are inert and nonmagnetic, they do not significantly influence the adhesive cure kinetics or particle heating behavior. In all cases where glass microspheres were used, loadings of 1%wt were added.

All filler materials were incorporated into the adhesive through hand mixing.

2.3 Lap Shear Testing

Lap shear samples were assembled using 0.125-in-thick Adiprene/woven glass composite adherends 1 in wide × 6 in long. A bond overlap of 1 in was used. The bond surfaces were lightly sanded and degreased prior to bonding. Mechanical tests were performed in an MTS Synergie (Cincinnati, OH) mechanical tester, using a 5 kN load cell and a loading rate of 0.04 in/min.

3. Equipment

3.1 Induction Equipment

For the phase I experiments, a water-cooled 2.5 kW Lepel model 7-2.5-1-MC5-BW induction power supply was used. The unit is rated for a tunable frequency range from 2.5 to 8 MHz. Manual tuning is performed using three internal adjustments. A two-position jumper determines whether the unit tunes within a range of low frequencies (2.5–5 MHz) or high frequencies (5–8 MHz). A 7-position tap setting varies the internal inductance. The internal capacitance is altered through swapping capacitors in an internal bank. Two control knobs on the unit exterior, each with a range from 0% to 100%, are labeled "Grid Control" and "Power Control." Grid Control provides additional fine tuning capability. Power Control scales the coil current, so that maximum coil current (and maximum field strength) is achieved at a Power Control of 100%. The Lepel unit also has four output meters, labeled "RF Current," "Grid Current," "Plate Current," and "Plate Voltage." According to the manufacturer, larger values of RF Current imply larger coil currents, although the exact value and proportionality of these currents is not known.

For the phase II experiments, a water-cooled Ameritherm NovaStar 1M 1.5 kW induction power supply was used. The unit is rated for a tunable frequency range from 10 to 15 MHz. System capacitance is adjusted through an internal bank of capacitors, as well as a mechanically tunable variable capacitor. A "Load Power" setting of 0–1500 W can be set manually. Larger values of Load Power produce larger output field strengths, although it is not clear whether these qualities are linearly proportional. The value of Load Power does not indicate the amount of power actually being transferred to the workpiece. Instead, it should be considered an indication of the relative induction field strength, independent of load.

For the Lepel unit, frequency measurements were performed using an Optoelectronics, Inc. (Ft. Lauderdale, FL) 3000A Plus frequency counter. For the Ameritherm unit, frequency values are measured internally and displayed as system output.

3.2 Induction Coils

Custom coils were constructed using 0.25 in outer diameter (OD) (0.030 in wall thickness) copper tubing. In some cases tubes were annealed between bending steps to allow tighter bend radii. All coils were coated with Sherwin Williams Co. (Solon, OH) S00600 dielectric insulating varnish to reduce the likelihood of arcing.

Three general types of induction coils were used: (1) pancake, (2) conventional solenoid, and (3) parallel solenoid. The pancake coil has a spiral in-plane geometry and is useful for imposing magnetic fields where only one-sided access is possible. This coil design is common in induction processing and was therefore used to initially benchmark particle and adhesive performance. For heating the cylindrical tube bondline, an axisymmetric coil is preferred. The solenoid is a simple and efficient coil geometry for generating axisymmetric fields.

To bond the composite tubes as quickly as possible, the solenoid coil must be designed to maximize the area of bondline heated. This consideration is not trivial due to the relatively large bond area in this application. The diameter of the coil is fixed at a size just large enough to fully encompass the tube diameter. The remaining design variables are the number of turns n in the coil and the length l of the coil. The magnetic field strength H_i at the center of the coil and inductance L_i of an ideal solenoid are given by

$$H_i = \frac{nI}{l} , \quad L_i = \frac{n^2 A}{l} , \tag{1}$$

where A is the cross-sectional area of the coil and I is the coil current. H must be kept high enough to provide adequate bondline heating, while L must be kept low enough to allow for proper tuning. An alternative design approach is to connect two identical solenoids in parallel. If each solenoid has an area A, length $l/2$, and $n/2$ turns, then the total effective magnetic field strength H_p and inductance L_p is

$$H_p = \frac{1}{2}\frac{nI}{l} , \quad L_p = \frac{1}{4}\frac{n^2 A}{l} . \tag{2}$$

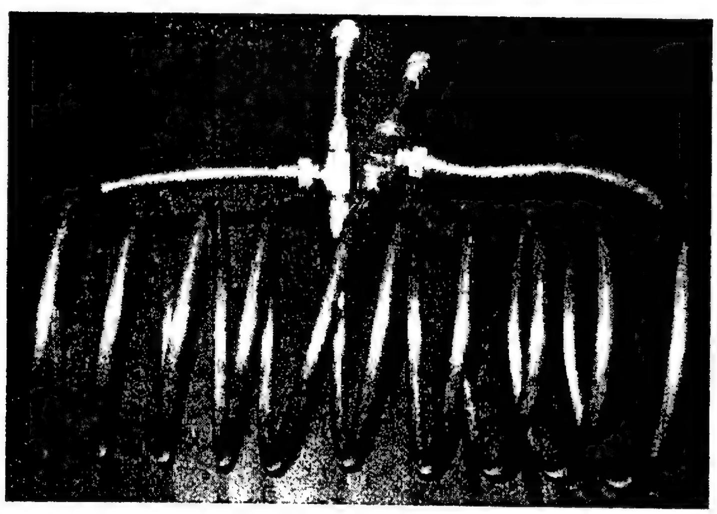
For inductance-limited tuning, this approach allows longer coils to be designed, although at the expense of lower field strength. We will use the notation "$m//m$" to signify a coil composed of two parallel solenoids each with m turns.

A wide range of coil geometries are considered during tuning of the Lepel power supply. However, most of the bonding experiments, both with the Lepel and Ameritherm units, focus on four specific coils: (1) a 3-in-diameter 3-turn pancake coil; (2) a 2-in-long 3-turn solenoidal coil; (3) a 4.5-in-long 4//4 solenoidal coil; and (4) a 9-in-long 5//5 solenoidal coil. These coils are shown in Figure 3. All solenoidal coils have a diameter of ~3.5 in. The 3-turn solenoid was the longest conventional solenoidal coil that we were able to fully tune with the Lepel unit. The 4.5- and 9-in parallel coils represent well-tuned parallel coils of increasing length.

(a) Pancake Coil

(b) 3-Turn Solenoid Coil

(c) 4//4 Solenoid Coil



(d) 5//5 Solenoid Coil

Figure 3. Coils used during many of the induction bonding experiments.

3.3 Temperature Sensors

Conventional thermocouples do not produce reliable measurements in induction fields due to electromagnetic interference and inductive heating of the sensor itself. One alternative is a fiber optic temperature sensor (FISO Technologies, Sainte-Foy, Quebec). The fiber optic sensor is very accurate and has a response time of under 0.1 s. However, it cannot be used for temperatures above 400 °C, it is extremely fragile, and costs around $350/sensor. In cases where the fiber optic sensor was not feasible, an AGEMA Infrared Systems (Secaucus, NJ) 900 Series infrared camera was used to perform temperature measurements. Because the infrared camera was not fully calibrated for each material and view angle under consideration, its temperature measurements can only be considered accurate to within 20 °C.

4. Phase I Experiments

Phase I experiments were performed at the University of Delaware using the Lepel induction power supply.

4.1 Tuning and Coil Design

A variety of tuning configurations were tested in order to determine the best settings for induction bonding. In general, the heating power generated in magnetic materials increases with induction field frequency and amplitude. Therefore, the optimum tuning configuration is the one that produces the highest values of frequency and RF Current.

For all tuning experiments, a 3-turn pancake coil was used, and the internal jumper was set to the high frequency position. Major tuning adjustment was performed by changing the tap position and bank capacitance. At a particular tap position and bank capacitance, the Grid Control setting was adjusted until maximum RF Current was achieved. In all cases, Power Control was set at 100% to produce maximum induction field strength.

Table 1 shows the output performance for a wide range of hardware configurations. For frequencies above 8 MHz, the measured frequency appeared to jump randomly so that a constant and consistent field strength output is not guaranteed. Setup 11, with a frequency of 6.28 MHz and an RF Current of 56 A, appears to be the best setup. The frequency is below 8 MHz, so consistent field strength is assured. This setup is used for all subsequent Lepel induction heating experiments.

Table 1. Hardware configurations and resulting performance for the Lepel induction power supply.

Setup No.	Tap Position	Capacitance (pF)	Power Control	Grid Control	Frequency (MHz)	RF Current (A)	Grid Current (A)	Plate Current (A)	Plate Voltage (kV)
1	6	100	100	0	—	a	a	a	a
2	6	350	100	0	7.9	46	170	0.42	4
3	4	350	100	20	6.1	40	160	0.42	4
4	4	250	100	20	7.1	30	200	0.40	4
5	4	100	100	20	9.2	30	240	0.64	4
6	5	100	100	35	11.1	34	240	0.52	4
7	5	350	100	15	6.9	48	180	0.44	4
8	5	450	100	13	6.5	50	160	0.48	4
9	5	700	100	13	5.1	50	160	0.48	4
10	6	700	100	6	5.9	56	110	0.50	4
11	6	600	100	5	6.3	56	120	0.52	4
12	6	450	100	5	7.1	51	160	0.48	4
13	4	450	100	18	5.5	44	160	0.38	4
14	4	600	100	20	4.8	49	145	0.39	4
15	4	700	100	19	4.5	50	140	0.40	4

[a]For setup 1, the system output was erratic, and no reliable values could be recorded.

Using this tuned Lepel setup, a variety of solenoid coils were tested. Table 2 shows the inductance, capacitance, resistance, and total impedance values for a number of coils, as measured using a Hioki 3522 LCR meter. Note that the LCR meter is only capable of making measurements of up to 100 kHz, which is below our expected operating frequency of 6 MHz. Table 3 shows the measured RF Current for some of these coils, for a Power Control setting of 100%. In all cases, the measured frequency was ~6.3 MHz. Figure 4 shows RF Current as a function of coil inductance. From the plot, it is clear that the output current increases as the coil inductance decreases. For the highest current case (3//3 coil), however, electrical crackling could be heard inside the unit. Therefore, the more conservative 3-turn, 4//4, and 5//5 coils were judged to be best suited for the bonding application.

4.2 Preliminary Heating Experiments

4.2.1 Pancake Coil

To downselect optimum adhesive/filler ratios for induction bonding, a series of preliminary experiments were performed using the 3-turn pancake coil.

The heating behavior of FP110 and FP95 powders was evaluated by placing ~5 g of each powder in a DuPont Kapton polymide film envelope. A fiber optic temperature sensor was embedded into the powder, and the envelope was insulated with ~1 cm of glass wool insulation. This insulated envelope was placed on a 3-mm-thick plaque of glass composite, which was then placed

Table 2. Measured inductance, capacitance, resistance, and total impedance values for various coil geometries.

Coil Geometry	Length (in)	f (kHz)	L (μH)	C (μF)	R (mΩ)	Z (mΩ)
3	2	10	1.3	200	2.4	79
		50	1.2	8.2	4.5	390
		100	1.2	2.1	3.1	770
4	2	10	1.8	140	3.4	120
		50	1.8	5.6	6.6	570
		100	1.8	1.9	11	1100
4	3	10	1.8	150	3.2	110
		50	1.7	5.9	6.4	540
		100	1.7	1.5	10	1100
4	4	10	1.6	160	3.1	100
		50	1.6	6.3	6.5	500
		100	1.6	1.6	10	1000
5	2.5	10	2.2	140	3.6	140
		50	2.1	4.6	6.5	680
		100	2.2	1.2	11	1400
8	9	10	3.9	64	6.0	250
		50	3.9	2.6	14	1200
		100	3.9	0.66	20	2400
15	9	10	8.2	30	12	0.52
		50	8.2	1.2	26	2.6
		100	8.2	0.31	35	5.1
3//3	6	10	0.75	330	2.0	47
		50	0.71	14	3.0	220
		100	0.69	3.7	4.0	440
4//4	4.5	10	1.2	200	3.0	80
		50	1.2	8.2	7.0	380
		100	1.2	2.1	9.0	770
5//5	9	10	1.2	220	2.2	72
		50	1.1	8.9	4.0	350
		100	1.1	2.3	2.0	710
8//8	9.5	10	2.3	110	4.0	1.4
		50	2.3	4.5	8.0	710
		100	2.3	1.1	12	1400

directly on top of the coil. The distance from the top of the coil to the center of the sample is ~8 mm. Figure 5 shows the heating behavior of the FP110 and FP95 powders. Both powders show relatively rapid heat and dwell behavior, achieving within 10 °C of their ultimate temperature in less than 1 min. The FP110 sample reaches an ultimate temperature of ~220 °C, while the FP95 sample reaches an ultimate temperature of ~180 °C.

Table 3. RF Current readings for various coils on the Lepel induction power supply.

Coil Geometry	Width (in)	L at 100 kHz (μH)	RF Current (A)
3	2	1.2	52
4	2	1.8	0
4	3	1.7	10
4	4	1.6	35
15	9	8.2	0
3//3	6	0.69	61
4//4	4.5	1.2	52
5//5	9	1.1	52

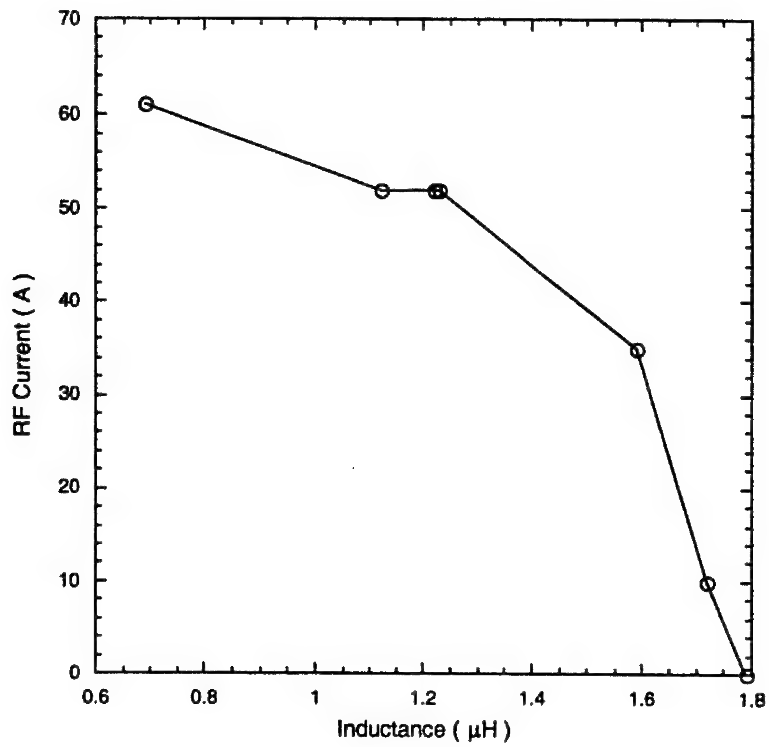


Figure 4. RF Current as a function of coil inductance for the Lepel induction power supply.

These heating behaviors represent the highest thermal efficiency scenario, insulated neat powders. In the actual bonding application, the powders will be dispersed in an adhesive, and spread as a thin layer on an adherend. To measure the heating behavior under these more realistic conditions, Adiprene adhesives were prepared with 10%vol FP110, and with 10%vol FP95. Layers of the

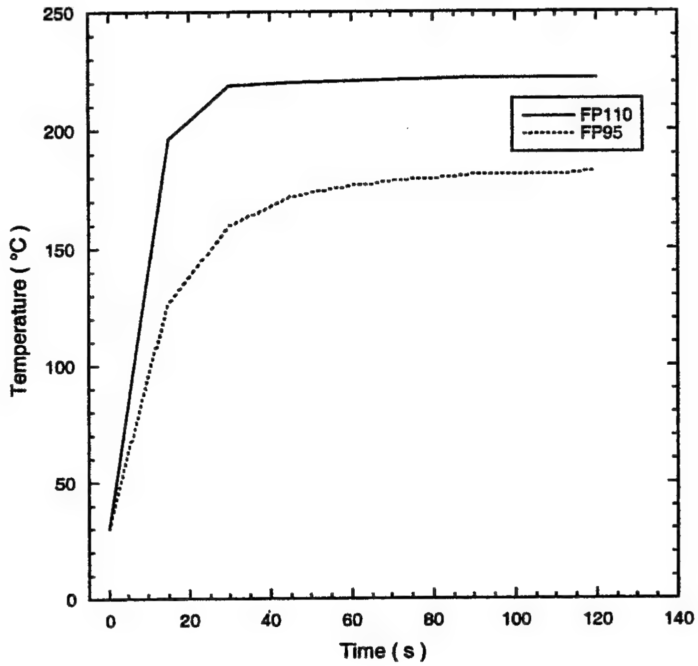


Figure 5. Heating behavior of insulated FP110 and FP95 powders in the Lepel induction power supply, using the 3-turn pancake coil.

adhesive were spread on the surface of a 3-mm-thick Adiprene/glass composite adherend, which was then placed directly on the pancake coil. Thick layers (~3 mm) of both adhesives were tested, as well as a thin layer (~0.5 mm) of the FP110 adhesive. Thermal histories were measured using the infrared camera.

Figure 6 shows the results of these adhesive heating experiments. The thick layers of adhesive exhibit rapid heat and dwell behavior, achieving within 10 °C of their ultimate temperature in less than 1 min. The FP110 adhesive sample reaches an ultimate temperature of ~150 °C, while the FP95 adhesive sample reaches an ultimate temperature of ~115 °C. Both temperatures are ~70 °C lower than the temperatures reached for the insulated powders alone. The thin layer of FP110 adhesive heats very gradually, taking over 5 min to reach 100 °C and still showing a moderate heating rate at 10 min. Comparing this behavior with the heating history for the thick layer of FP110 adhesive and the insulated FP110 powder gives a broad view of the significance of efficiency losses associated with the typical adhesive bonding geometry. These heating rates are compared quantitatively in Table 4. The behavior of the thin adhesive layer also shows that the rapid heat and dwell behavior possible for Curie temperature—limited heating will only be observed if the generated induction power greatly overmatches thermal losses.

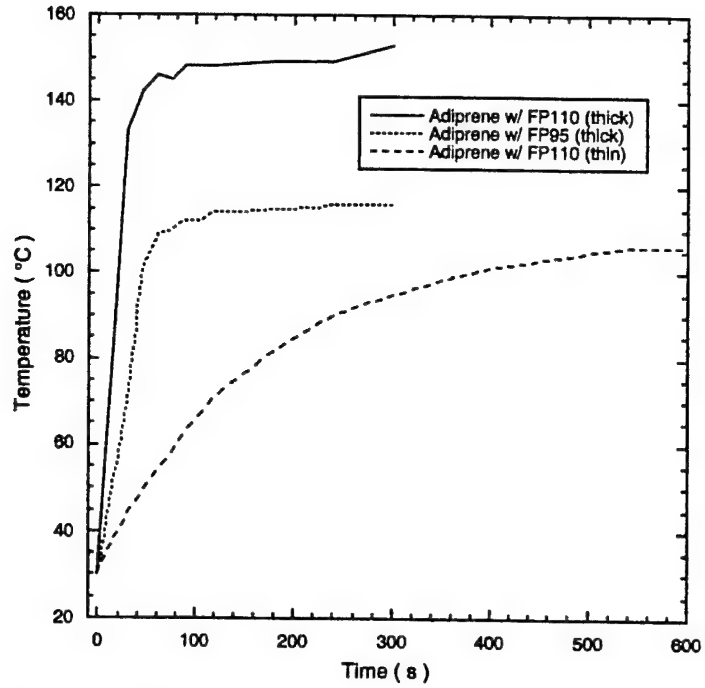


Figure 6. Heating behavior of Adiprene adhesive with 10%vol FP110 and FP95 powders, in the Lepel induction power supply with the 3-turn pancake coil.

Table 4. Comparison of heating rates for neat FP110 powder and 10%vol FP110 powder in adhesive, for the Lepel induction power supply with the 3-turn pancake coil.

Material	Temperature at 15 s (°C)	Average Heating Rate (°C/s)
Neat FP110	196	11.07
FP110 in Adhesive (Thick Layer)	80	3.33
FP110 in Adhesive (Thin Layer)	38	0.53

4.2.2 Solenoid Coil

Figure 7 shows the heating behavior of FP160 in the 5//5 solenoid coil, measured using the same insulated Kapton envelope approach described in section 4.2.1. The sample shows clear heat and dwell behavior, reaching an ultimate temperature of ~175 °C. In identical induction fields, we would expect the FP160 material to heat to higher temperatures than the FP110 or FP95, due to its higher Curie temperature (as specified by the manufacturer). However, the temperatures reached by the FP160 in the 5//5 coil are less than or comparable to the temperatures reached by the FP95 and FP110 powder in the 3-turn pancake coil (see Figure 5). Therefore, we can infer that the field strength produced in the 5//5 coil is less than that produced by the 3-turn pancake coil. This result is consistent with the theoretical coil relations of section 3.2.

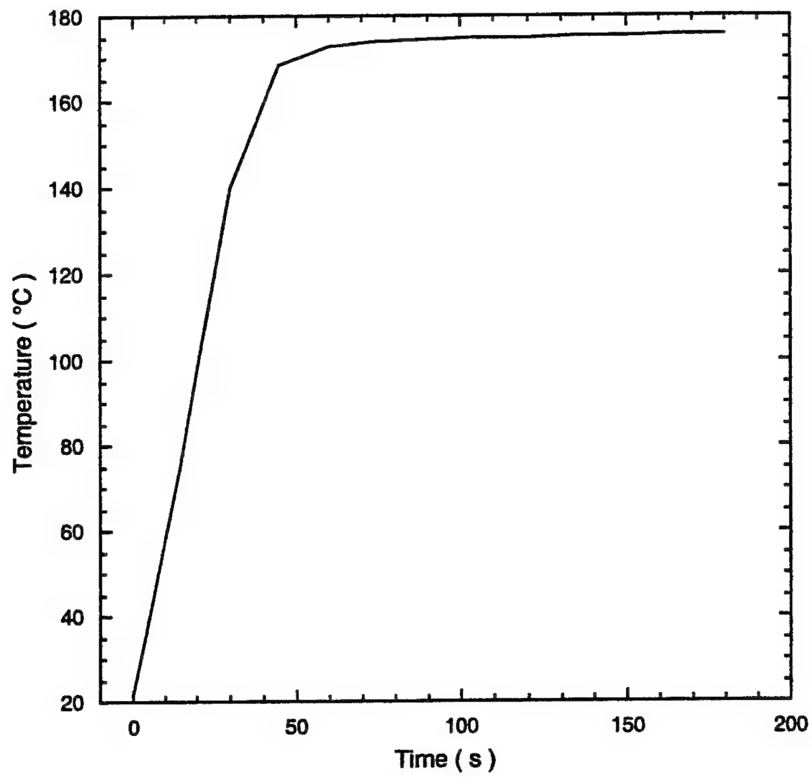


Figure 7. Heating behavior of insulated FP160 powder in the Lepel induction power supply, using the 5//5 solenoid coil.

4.3 Preliminary Bonding Experiments

Bonding experiments were run in 3-turn, 4//4, and 5//5 solenoid coils to better model process performance during tube bonding. In all cases, the adhesive was loaded with 20%vol FP160. This volume fraction represents an approximate upper bound on filler content that allows complete mix wetting and incorporation into the adhesive. Glass microspheres were incorporated into most of the adhesives, although the particle size was reduced in later runs. A variety of adherends were bonded to approximate the final bonding geometry. Two types of conventional planar adherends were used. "Thin" adherends are roughly 0.125 in thick and 1 in wide, while "thick" adherends are roughly 0.1875 in thick and 1 in wide. These different adherend thicknesses are intended to represent the range of effective adherend thicknesses which occur over the length of the final tapered tube joint. The planar samples were bonded in lap shear geometries, although the large amount of overlap is some cases is unconventional. The samples were placed inside the solenoidal coils on a piece of 0.005-in-thick Kapton film set directly on the coil, to closely match the bondline position expected during final tube bonding. Minitubes, as described in section 2.1, were also bonded. For cases where the bondline overlap is longer than the coil length, the bondline was indexed through the coil in a stepwise manner.

Table 5 shows results from these experiments. In general, bonding with the 3-turn coil was successful, while bonding with the 4//4 and 5//5 coils was unsuccessful. One possible reason why the parallel coils are unable to produce complete bonding is inadequate field strength, since the parallel coils have winding currents equal to one-half of the input current. To test this theory, a bonding run was performed using the 3-turn coil at one-half of the Lepel full current value (run 4 in Table 5). Since the 3-turn and 5//5 coils have approximately the same number of turns per unit length, this experiment should simulate the magnetic field strength produced by the 5//5 coil operating at full current (although the field is produced over a much reduced area). As expected, this run produced an unbonded sample. Further confirmation of this field theory is found in the results of the 4//4 coil, which produced partially bonded samples (runs 5 and 6 in Table 5). This coil has a moderately higher turn density than the 5//5 coil, so it should produce a moderately higher field strength for the same input current. This difference in field strengths explains why the 4//4 coil bonded the samples slightly more effectively than the 5//5 coil.

Table 5. Results of bonding runs for the Lepel induction power supply.

Run No.	Coil Geometry	Coil Length (in)	RF Current (A)	Glass Microspheres wt%, size	Adherend Geometry, Overlap	Time (No. Steps at Time per Step)	Result
1	5//5	9	52	0%	Thin/Thin, 1 in	10 min	Not Bonded
2	5//5	9	52	1%, 500 µm	Thin/Thin, 1 in	15 min	Not Bonded
3	3	2	52	1%, 500 µm	Thin/Thin, 1 in	15 min	Bonded
4	3	2	26	1%, 500 µm	Thin/Thin, 1 in	15 min	Not Bonded
5	4//4	4.5	51	1%, 300 µm	Thin/Thin, 9 in	2 at 10 min	Semi-Bonded
6	4//4	4.5	51	1%, 300 µm	Thin/Thin, 1 in	10 min	Semi-Bonded
7	3	2	52	1%, 300 µm	Thin/Thin, 3 in	3 at 10 min	Bonded
8	3	2	52	1%, 300 µm	Thin/Thin, 3 in	3 at 10 min	Bonded
9	3	2	52	1%, 300 µm	Thin/Thin, 6 in	6 at 10 min	Bonded
10	3	2	52	1%, 300 µm	Thin/Thin, 9 in	10 at 10 min	Bonded

These results indicate that with the Lepel induction power supply, only the 3-turn coil is capable of producing fully bonded joints for the adhesive and adherend materials under consideration. For this 3-turn coil, bonding is best performed in 1 in increments, with 10 min of field exposure per increment.

4.4 Final Bonding Run

Based on the results of the preliminary experiments, Adiprene resin with 20%vol FP160 and 1%wt 300 µm glass microspheres was selected as the adhesive for the final tube bonding run. Both tube bond faces were lightly sanded and degreased with acetone, and then evenly coated with the adhesive. The tubes were forced together, and the excess adhesive flash was wiped off, both at the internal and external joint butts. The viscoelastic properties of the adhesive tended to force the compressed joint apart longitudinally, so mechanical restraint was used to hold the tubes together during the first few minutes of bonding.

The tube was bonded in the Lepel unit using the 3-turn solenoid coil. The coil is ~2 in long, while the tube bond area is ~9 in long. The bond area was fed through the coil in a series of 10 steps of 1 in of displacement each with a process time of 10 min/step. Some tube rotation may have also occurred between each step. The total bonding time was ~100 min. Figure 8 shows the bonding process in progress.

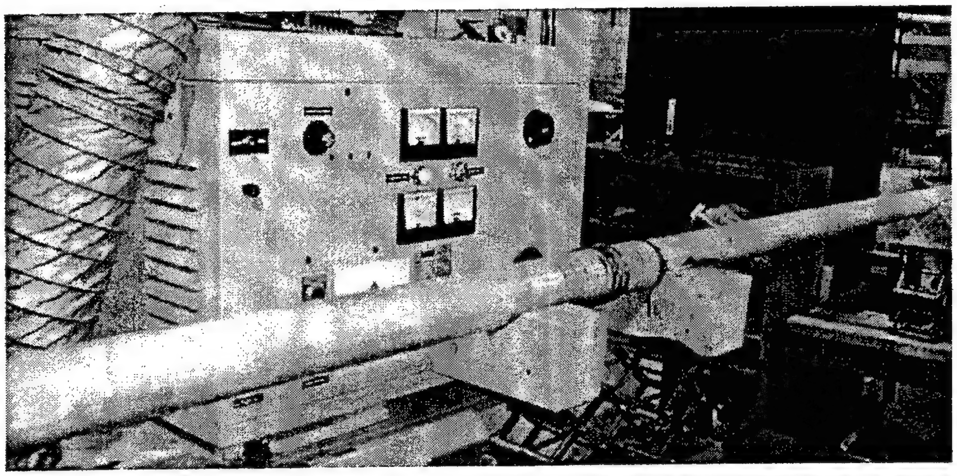


Figure 8. Induction bonding of full tubes using Lepel induction unit.

After bonding, the tube was allowed to cool and was then inspected. The flash was fully cured. The joint could not be separated by twisting or pulling on the tubes by hand.

This tube is shown in Figure 9. Figure 10 shows the cross section of the minitube bonded under the same protocol, which we expect looks very similar to the cross section of the final bonded tube.

5. Phase II Experiments

Phase II experiments were performed at ARL, using the Ameritherm induction power supply.

5.1 Tuning and Coil Design

The same 3-turn, 4//4, and 5//5 solenoid coils used in the phase I experiments were used with the Ameritherm unit in the phase II experiments. With a 100 pF capacitor, these three coils tuned at 12.78, 12.75, and 12.92 MHz, respectively. For each coil, the unit was capable of being operated over its full range of Load Power, from 0 to 1500 W, with only minor changes in frequency.

Figure 9. Final bonded tube for phase I experiments.

5.2 Preliminary Heating Experiments

Figure 11 shows temperature histories for FP160 in the 3-turn, 4//4, and 5//5 solenoid coils at Load Power settings of 100, 500, and 1500 W. These measurements were performed using a fiber optic temperature sensor embedded in an insulated envelope of 5 g of powder, identical to the setup described in section 4.2.1. The 3-turn solenoid heats the powder faster than the parallel coils, and the 4//4 coil heats the powder faster than the 5//5 coil. Heating rates are higher at higher power levels. Note that, even for the 100 W setting and the 5//5 coil, the powder heats to 100 °C in under 1 min. As a rough comparison of heating rates, Table 6 shows the temperature of the powder at a time of 30 s, for both the Ameritherm unit and the Lepel unit (see Figure 7). In all cases, in Table 6 the 5//5 coil was used to generate the induction field. The Lepel unit, operating at full power, heats the powder at a rate comparable to the

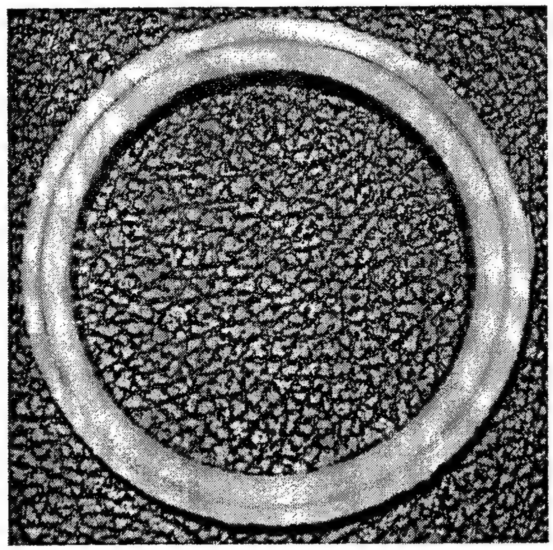


Figure 10. Cross section of bonded minitube for phase I experiments.

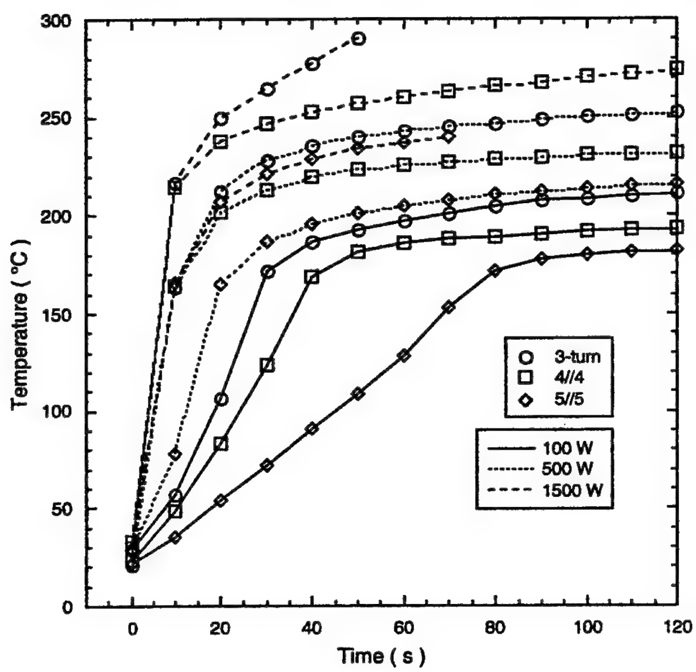


Figure 11. Heating behavior of insulated FP160 powder in the Ameritherm induction power supply, using various coils and power levels.

Ameritherm unit operating at between 100 and 500 W. The Ameritherm unit operating at full power heats the powder approximately twice as fast as the Lepel unit operating at full power.

Table 6. Comparison of heating rates for insulated FP160 powder in the Lepel and Ameritherm induction power supplies, with the 5//5 solenoid coil.

Induction Unit	Power Setting	Temperature at 30 s (°C)	Average Heating Rate (°C/s)
Lepel	100%	140	3.67
Ameritherm	100 W	70	1.33
Ameritherm	500 W	180	5.00
Ameritherm	1500 W	220	6.33

Special lap shear specimens were prepared to allow for direct measurement of representative bondline temperature histories. The adherends were Adiprene/woven glass composite 0.125 in thick × 1 in wide × 6 in long. A 0.0625-in-wide × 0.0625-in-deep × 1-in-long groove was cut into one of the adherends in the bondline area, as shown in Figure 12. A thin layer of Kapton film was placed over this groove, and then the adherends were bonded together. The samples were bonded using a 1 hr oven cure at 120 °C, using Adiprene with 20%vol FP160 and 1%wt 300 μm glass microspheres as the adhesive. Once bonded, a fiber-optic temperature sensor was inserted into the groove, and induction heating experiments were performed. Note that the groove width and depth dimensions provide a tight fit for the fiber optic sensor, so that the sensor is well insulated and in good thermal contact with the adhesive bondline. Also note that, because the adhesive is precured, these experiments only measure the heating effect due to the magnetic particles and do not include any exothermic heating due to the adhesive cure reaction.

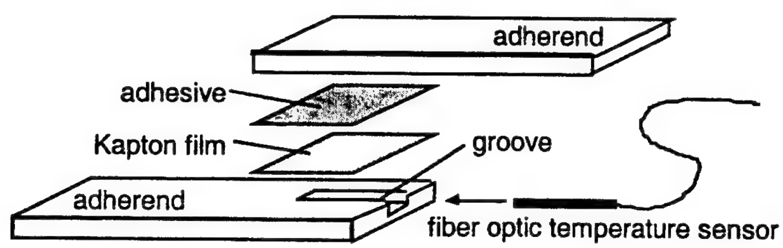


Figure 12. Assembly geometry for measuring lap shear bondline temperature histories.

Figure 13 shows the lap shear temperature histories for power settings of 500, 1000, and 1500 W, using the 5//5 solenoid coil. The ultimate temperatures reached for each case are ~160°, 180°, and 210 °C, respectively. These temperatures are lower than the temperatures reached for the neat powder (see Figure 11), but are still well above the required cure temperature of 120 °C.

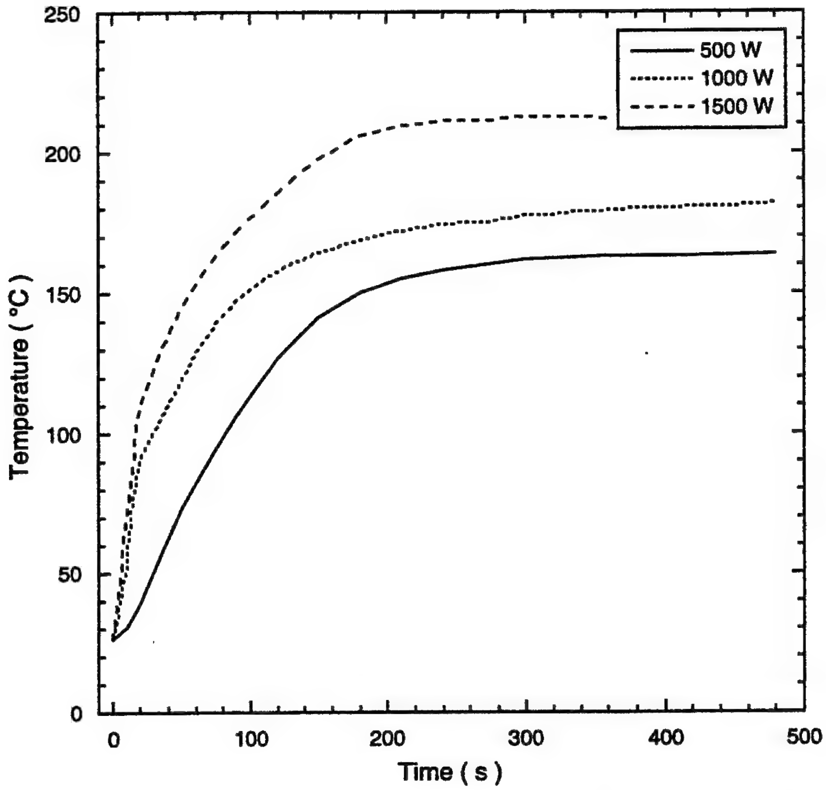


Figure 13. Temperature history for lap shears bonded with 20%vol FP160, using the Ameritherm induction power supply with the 5//5 solenoid coil at various power levels.

5.3 Preliminary Bonding Experiments

5.3.1 Lap Shear Strength Specimens

The effect of filler volume fraction on bond strength was investigated to determine acceptable filler loadings. Lap shear specimens were bonded using Adiprene with loadings of 0%, 5%vol, 10%vol, and 20%vol FP160. All samples also contained 1%wt 300 μm glass microspheres and were oven-cured at 120 °C for 1 hr. Five samples of each adhesive formulation were bonded and mechanically tested. Table 7 and Figure 14 show the results. Lap shear strength increases with increasing filler content, with the strength at 20%vol FP160 ~50% higher than the sample with no filler. In all cases, failure was mostly cohesive in the adherend, located directly below the bondline. The increasing strength with filler content is probably due to a stiffening effect in the adhesive, which may improve load transfer and decrease peel stresses. Since high bond strengths are achievable at the highest filler loading, and heating power increases with increasing filler loadings, 20%vol FP160 was used for all subsequent bonding experiments.

Table 7. Lap shear strength data for oven-cured Adiprene with various volume fractions of FP160 powder. All failures were cohesive in the adherend.

Vol% Filler	Lap Shear Strength Average ± Standard Deviation (MPa)
0%	3.61 ± 0.70
5%	4.54 ± 0.64
10%	5.46 ± 0.55
20%	5.84 ± 0.89

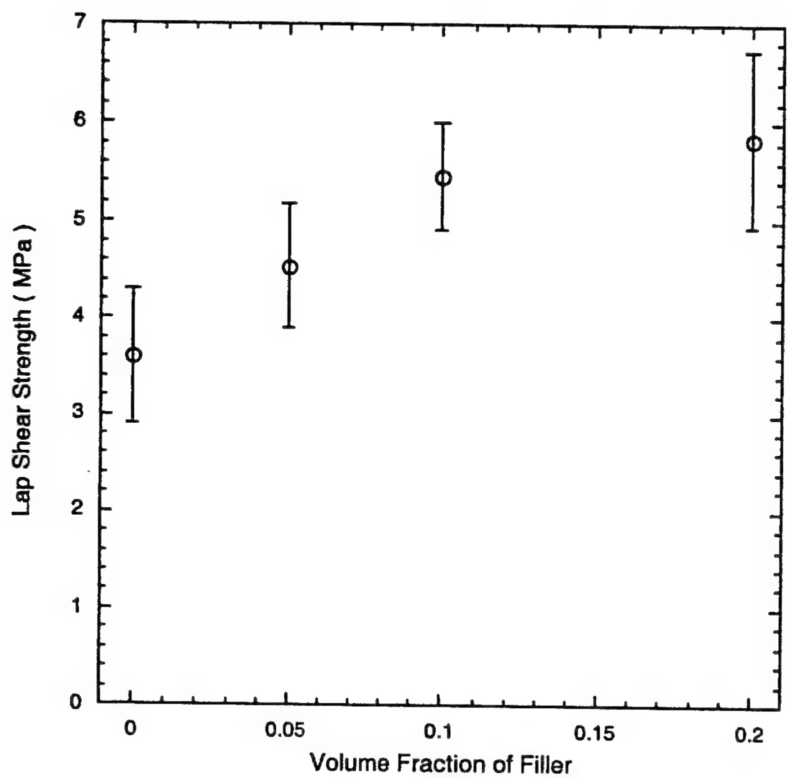


Figure 14. Effect of volume fraction of FP160 powder on lap shear strength for oven cured Adiprene adhesive. Error bars show ± standard deviation.

The effect of processing conditions was investigated using lap shear specimens bonded with 20% vol FP160 in Adiprene, with 1%wt 300 μm glass microspheres. In addition to oven-cured samples, lap shears were processed in induction fields at settings of 500, 1000, and 1500 W for 5–30 min. All induction samples were processed using the 5//5 coil, with the lap shear bond area centered laterally in one of the two parallel coils (Figure 15), and placed inside the coil on a piece of 0.005-in-thick Kapton film set directly on the coil. This location closely matches

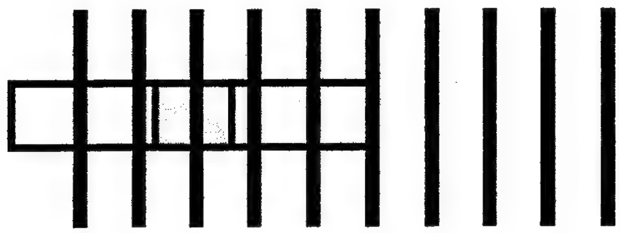


Figure 15. Position of lap shears in 5//5 solenoid coil during processing.

the bondline position expected during the final tube bonding. Because Adiprene is susceptible to gelling at room temperature, all samples were mechanically tested within 6 hr of bond processing. Five samples of each processing condition were bonded and mechanically tested, except for the 500 W samples for 20 min and 30 min, for which only four samples were tested.

Table 8 and Figure 16 show the lap shear strengths for these specimens. Note that none of the induction-cured samples reach the full oven-cured strength, although at 500 W for 20 min and 30 min the average strengths are only 20% below the oven-cured samples. Also note that, for the 500 W samples at 20 min and 30 min, failure is mostly in the adherend. At 1500 W, increasing cure time causes a decrease in average lap shear strength. This trend implies that thermal degradation is occurring at this power level. This result is consistent with the temperature measurements (see Figure 13) which showed that temperatures as high as 210 °C were reached at 1500 W, which is well above the recommended cure temperature.

Table 8. Lap shear strength data for induction-cured Adiprene with 20%vol FP160.

Process Conditions	Failure Mode	Lap Shear Strength Average ± Standard Deviation (MPa)
500 W for 10 min	Cohesive[a]	2.32 ± 0.70
500 W for 20 min	Adherend[b]	4.81 ± 0.47
500 W for 30 min	Adherend	4.75 ± 0.68
1000 W for 10 min	Cohesive	2.47 ± 0.38
1500 W for 5 min	Cohesive	2.78 ± 0.23
1500 W for 10 min	Cohesive	2.31 ± 0.70

[a]Cohesive indicates a cohesive failure within the adhesive.
[b]Adherend indicates a cohesive failure in the adherend.

Although the maximum induction lap shear strengths are not as high as the oven-cured filled sample, the values still exceed the lap shear strength of the unfilled Adiprene adhesive (see Figure 13). This strength is considered adequate for the final tube prototype application. Note that, unlike the Lepel induction power supply, the Ameritherm induction power supply with the 5//5 coil

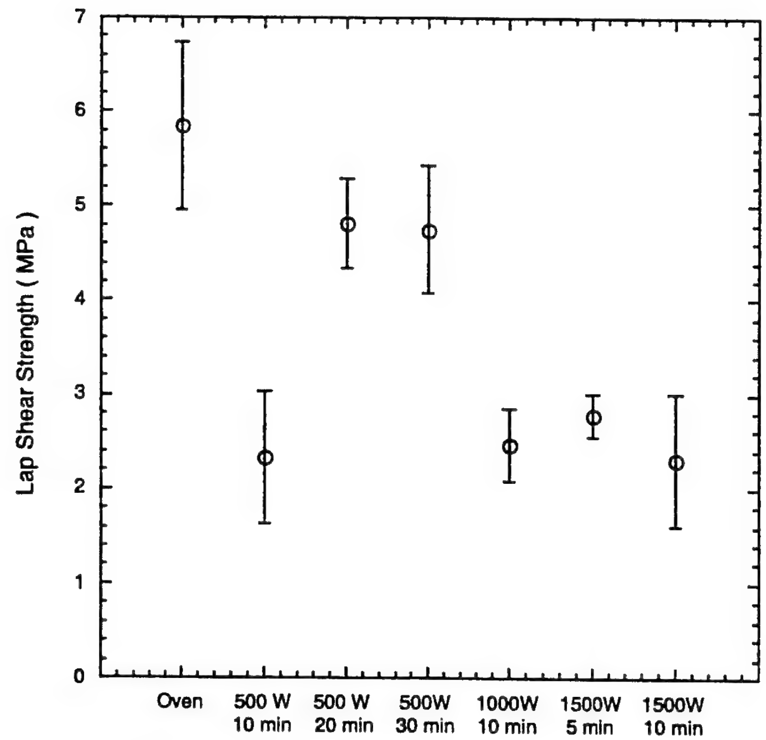


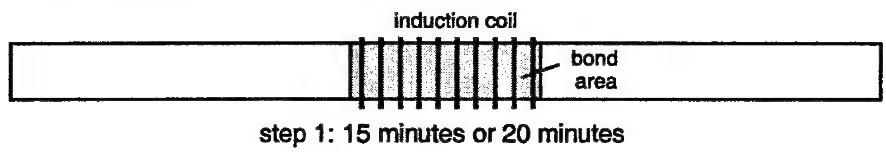
Figure 16. Effect of processing conditions on the lap shear strength of samples bonded using 20%vol FP160. All samples were induction cured using the Ameritherm induction power supply, except for the oven-cured sample. Error bars show ± standard deviation.

produces adequate heating for adhesive bonding. In fact, the strength data may indicate that at full power the generated heating at the bondline exceeds allowable levels. Due to the large area over which this coil generates induction fields, the success of the 5//5 coil provides an opportunity to bond the final tube bondline much faster than was possible with the Lepel induction power supply.

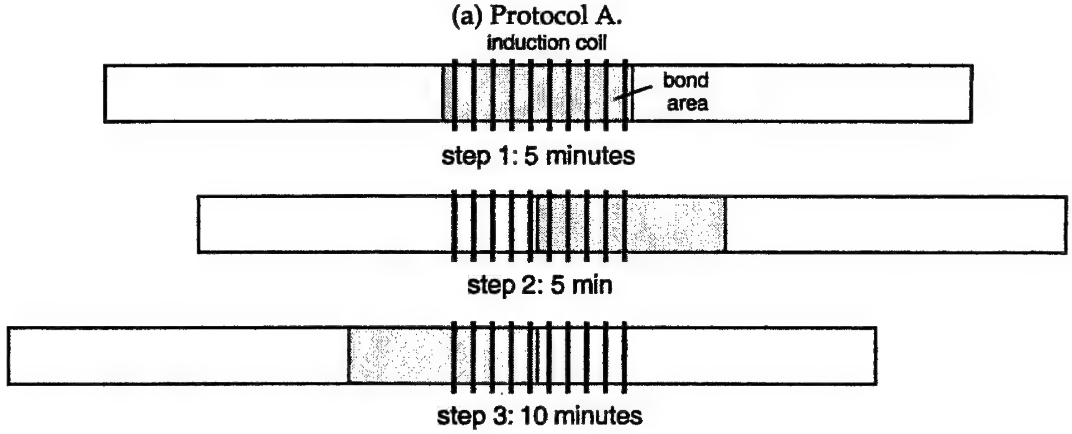
5.3.2 Large Bond Area Specimens

Bonding experiments were run in the 5//5 coil to determine optimum conditions for tube bonding. "Thick" 0.1875-in-thick × 1-in-wide and "thin" 0.125-in-thick × 1-in-wide planar adherends were used. The adherends were bonded with 9-in-long bondlines, to simulate the length of the final tube bondline. The samples were placed inside the solenoidal coil on a piece of 0.005-in-thick Kapton film set directly on the coil, to closely match the bondline position expected during final tube bonding. Minitubes, as described in section 2.1, were also bonded. All Adiprene adhesives contained 20%vol FP160 and 1%wt 300 μm glass microspheres.

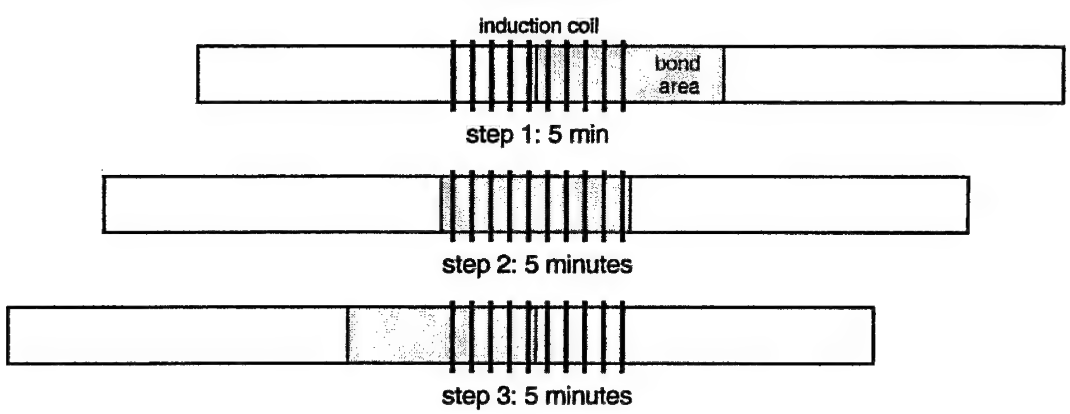
Three different positional protocols were investigated, labeled A, B, and C in Figure 17. Protocol A is stationary, with the 9 in bondline centered in the 90 in coil. Protocol B is a 20 min protocol, beginning with 5 min centered on the coil, then 5 min off-center to the right, and then 10 min off-center to the left. The last stage is given extra time because of the significant cooling which occurs to the far right of the sample during the second 5 min stage. Protocol B is an inefficient approach and was replaced by protocol C. Protocol C involves three 5 min stages, with the bondline displaced by one-half of its length in the same direction in each step. Note that in protocol C, each area of the bond is exposed to the induction field for 10 consecutive min.



(a) Protocol A.



(b) Protocol B.



(c) Protocol C.

Figure 17. Position vs. time protocols for bonding runs from Table 9.

Table 9 shows the results of these tests. The first minitube, processed at 500 W with protocol A (run 1), appeared well bonded after processing. However, also evident was a series of large blisters inside the tube, ranging from 0.5 to 1.5 in in diameter. The second minitube, initially heated at 500 W and then reduced power levels (run 2, also Figure 18), was also well bonded. The reduction in power levels decreased the severity of blistering, but some small blisters were still evident. In runs 3–5, planar adherends were bonded at 500 W using protocol B. All samples were well bonded. However, all of the samples had thin strips on the adherends, within a few inches of the bondline, that appeared more visually translucent than the virgin matrix (see Figure 17). There was also evidence of matrix flow at the adherend edges near this thin strip, where it appeared that matrix resin had "oozed" out of the adherend. The translucency and flow are evidence of matrix material melting. We expect matrix material melting to be detrimental to the mechanical performance of the composite, so the power level was reduced. Runs 6–8 were performed on planar adherends at 400 W using protocol C. All adherends were well bonded, with no signs of melting. Run 9, performed on planar adherends at 300 W and using protocol C, produced a partial bond with no evidence of melting. A minitube was then bonded at 400 W using protocol C, producing a well-bonded tube with no blistering. This approach, 400 W and protocol C, was adopted for the final tube bonding runs.

Table 9. Results of bonding runs for the Ameritherm induction power supply.

Run No.	Power (W)	Adherend Geometry	Time (min)	Protocol[a]	Result
1	500	Minitube	15	A	Bonded, Blistered
2	500–150[b]	Minitube	20	A	Bonded, Blistered
3	500	Thin/Thin	20	B	Bonded, Some Melting
4	500	Thin/Thick	20	B	Bonded, No Melting
5	500	Thick/Thick	20	B	Bonded, No Melting
6	400	Thin/Thin	15	C	Bonded, No Melting
7	400	Thin/Thick	15	C	Bonded, No Melting
8	400	Thick/Thick	15	C	Bonded, No Melting
9	300	Thin/Thin	15	C	Semi-Bonded, No Melting
10	400	Minitube	15	C	Bonded, No Blistering
11	400	Final Tube	15	C	Bonded, No Blistering
12	400	Final Tube	15	C	Bonded, No Blistering

[a] Bonding protocol details are given in Figure 17.

[b] Full power vs. time profile is given in Figure 18.

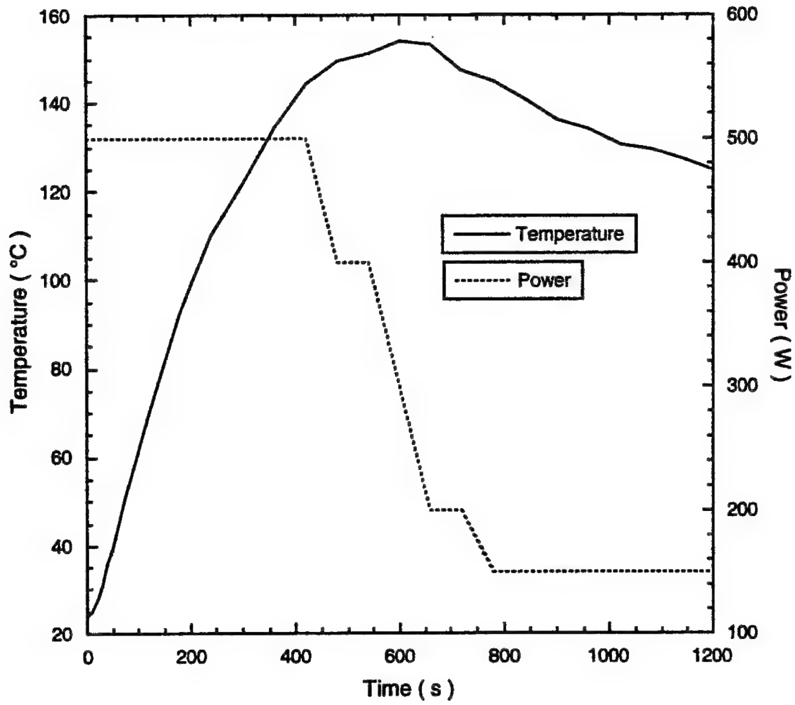


Figure 18. Power vs. time profile for minitube bonding run 2 in Table 9. Also shown is the temperature on the inner surface of the tube at the longitudinal center of coil, as measured using the fiber optic temperature sensor.

Note that, using protocol C and 400 W, each area of the bond is subjected to 400 W for ~10 min. According to our earlier lap shear strength data (Figures 13 and 15), under these conditions the actual bond strength may be less than the standard oven-cured bond strength. However, we expect that there are less thermal losses during tube bonding than during conventional lap shear bonding, since the large bond area eliminates many of the lap shear end effects. Therefore, tube processing at 400 W probably corresponds to lap shear processing at higher power levels. Direct mechanical testing of these tube bonds would be necessary to determine if full strength is truly achieved.

5.3.3 Adiprene Self-Heating Experiments

During the preliminary bonding runs of section 5.3.2, tube blistering and planar adherend melting were observed. Both effects are likely evidence of some form of matrix softening, in which the matrix begins to flow. In the case of the tubes, this softening causes blistering due to the residual radial stresses induced during filament winding. In the case of planar adherends, the effect is to allow local flow and changes in the appearance of the matrix. In all cases, both the blisters and melting occurred over a very thin (~0.5 in) strip of material. This strip of material was always located at the very center of the 5//5 coil, as shown in

Figure 19. This local melting was also observed in the lap shear strength specimens of section 5.3.1, in which the melting zone was located several inches away from the inductively heated bondline.

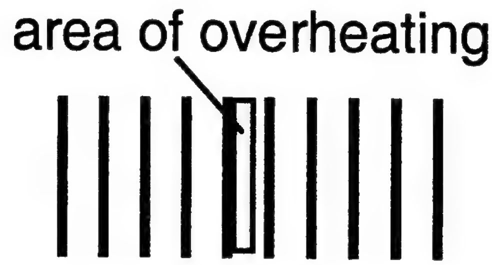


Figure 19. Location of area of overheating during high power bonding using the 5//5 solenoid coil in the Ameritherm induction power supply.

One possible cause of softening is excessive heating of the matrix. To determine if heating was the cause of softening, a fiber optic temperature sensor was placed on a minitube, centered in the 5//5 coil, with no adhesive. The resulting temperature history at 500 W is shown in Figure 20.

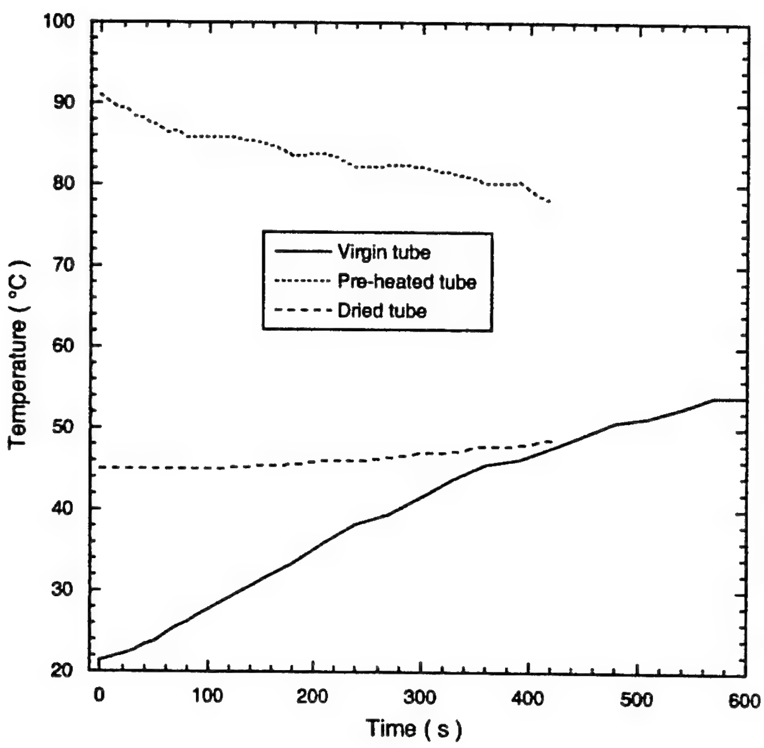


Figure 20. Comparison of heating behaviors of glass fiber/Adiprene composite minitubes with no adhesive, in the Ameritherm induction power supply with the 5//5 solenoid coil at 500 W.

The tube heats by ~25 °C in 10 min. To determine if the rate of heating is higher at higher tube temperatures, a tube was preheated to 100 °C and placed in the 5//5 coil, again at 500 W. In this case, tube heating was not evident, and the tube merely cooled towards ambient temperature. A third tube was dried at 120 °C for 4 hr, then placed in the 5//5 coil at 500 W. In this case, very slow heating was observed.

These results are discussed further in section 6.3.

5.4 Final Bonding Run

Based on the results of the preliminary bonding experiments, 20%vol FP160 in Adiprene with 1%wt 300 μm glass microspheres was chosen as the final bonding adhesive. The mating tube surfaces were lightly sanded and degreased with acetone prior to bonding. The adhesive was spread evenly on both surfaces, which were then forced together. Excess adhesive was wiped clean before bonding.

The tubes were bonded using the 5//5 coil at a setting of 400 W, using protocol C. The tubes were rotated by 90° halfway through each of the three steps in the protocol. The total bonding time was 15 min. Two sets of tubes were bonded in identical fashion. Figure 21 shows the bonding process in progress.

Figure 21. Induction bonding of full tubes using the Ameritherm induction unit.

After bonding, the tubes were allowed to cool and were then inspected. The flash was fully cured. The joint could not be separated by twisting or pulling on the tubes by hand. These tubes are shown in Figure 22.

6. Discussion and Conclusions

6.1 Equipment Considerations

Comparison of the phase I and phase II experiments demonstrates the importance of induction power supply characteristics for enabling bondline heating using magnetic particles. The Lepel unit, with its restricted tunability

Figure 22. Final bonded tube for phase II experiments.

and limited magnetic field strength output, was not capable of generating adequate heating power over large areas. The Ameritherm unit, on the other hand, was able to heat very large areas at only a fraction of its full power capabilities. The success of the Ameritherm unit can be attributed both to its advanced auto-tuning characteristics, as well as its relatively high frequency of operation. It is also important to note that this unit has only been commercially available since 1999. Earlier researchers, who concluded that induction bonding using magnetic particles was infeasible, were restricted to much less

sophisticated equipment, such as the non-water-cooled, 50 kHz unit used by Hahn et al. (1991).

The Lepel tuning experiments and heating rate comparisons underscore the importance of proper coil design, especially for large bond areas. Achieving large areas of field coverage with reasonable spatial uniformity must be balanced with tuning considerations. In fact, the 3-stage, 15 min process used for the final tube bonding in phase II could probably be simplified even further through improved coil design. A single stationary bonding step was not possible with the 5//5 coil because its length (9 in) was identical to the length of the bond area. Centering the bond within the coil produced non-uniform heating, due to fringing effects at the ends of the coil. It is likely that a longer (e.g., 12 in) coil could have been designed which would have allowed a single stationary bonding step, perhaps reducing the 15 min process to only 10 min.

6.2 Material Considerations

While the final bonding demonstration was successful, the adhesive and magnetic materials used were far from optimal. The lap shear strength data indicates that full strength is not achieved until the adhesive is heated for 20 min, even at higher processing temperatures. This limitation prevents full utilization of the rapid heating provided by induction processing. It is possible that through customization of adhesive chemistries, full strength bonds can be achieved in much less time.

The magnetic materials used in these experiments were also far from optimum. These soft ferrites were used because they are commercially available, although not intended for induction heating applications. The primary limitations of these materials are their low energy density and poor Curie temperature behavior. Higher energy density materials would allow adhesive formulations with lower magnetic particle loadings. Full utilization of Curie temperature control would prevent bondline overheating and allow more rapid heating. These features would reduce process times and improve thermal uniformity. In fact, the potential for improved thermal uniformity would also simplify coil design, since the bondline thermal history would be much less sensitive to local variations in induction field strength. We have already designed improved magnetic materials and demonstrated their superior heating performance (Wetzel et al. 2000). We hope to scale-up production of these materials and utilize them in subsequent induction bonding applications.

6.3 Adiprene Self-Heating Phenomenon

The Adiprene self-heating experiments (section 5.3.3) provide a number of confounding results. Most importantly, the self-heating of a non-conductive, non-magnetic glass fiber/polymer composite at submicrowave frequencies is completely puzzling. At these low MHz frequencies, typically only conductive

and magnetic heating mechanisms can produce heating, as is the case with carbon-fiber composites and magnetic particle-loaded adhesives. Most glass fiber/polymer composites will show absolutely no heating at these frequencies. Some polymers will heat significantly at microwave (GHz) frequencies due to dielectric mechanisms. These same dielectric mechanisms are active at the lower inductive frequencies, but their magnitude is rarely, if ever, large enough to produce a measurable heating effect.

A second puzzling effect is that the two minitubes that blistered were subject to the same 500 W field as the unbonded tubes in Figure 18. However, after 10 min in the field, the unbonded tubes only self-heated by 25 °C. This small temperature rise would not be expected to be significant enough to cause blistering during a bonding run. It is possible that the combined effect of adhesive heating and Adiprene self-heating caused the local overheating that led to blistering. However our preheated, unbonded tube (Figure 18) did not show significantly accelerated heating. In fact, it did not appear to heat at all. Perhaps there are more subtle thermal and moisture interaction effects at work.

The extremely localized nature of the overheating is also puzzling. Overheating always occurred in a very thin strip of material located at the very center of the coil. In fact, the strip of material seemed to lie directly below the center coil winding and had the same width as the copper tubing. The center of the coil could be the location of the highest induction field strength. However, with the parallel solenoid coils, the center of the coil is also the boundary between the end of one semi-coil and the beginning of the second semi-coil. This transition may play a role in the localized heating. At the center of the coil, there will be a large potential gradient between the two semi-coils, since one semi-coil is at its highest local potential while the other is at its lowest local potential. This potential gradient should produce an electric field, which will oscillate at the induction operating frequency. It is possible that this electric field causes dielectric heating in the polymer. We are not sure how to modify the parallel induction coil design to alleviate these effects, or what other material systems will be susceptible to it.

6.4 Future Applications of Induction Heating

Although there is significant room for process improvement, both in terms of material and equipment, the tube bonding demonstrations confirm the feasibility of using induction processing for rapid curing of large, structural bonds. The experiments also show that magnetic particle susceptors are viable alternatives to traditional metallic susceptors. In fact, recent advances in magnetic particle susceptor design should lead to significant process improvements which will make this approach clearly superior to other induction bonding approaches. We also expect that continuing process demonstrations will lead to wider application of this technology to other Army and Department of Defense systems, including composite structural manufacturing and repair.

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Large structural composite tubes, prototype components for a proposed U.S. Navy application, are bonded by induction curing of an engineering adhesive. Magnetic powder is used as the susceptor material and is directly incorporated into the adhesive prior to processing. Different induction power supplies, coil designs, and adhesive formulations are investigated. Final demonstration runs bond 9-in-long, 3-in-diameter axisymmetric bondlines in 15 min. These results demonstrate for the first time the successful induction bonding of large structural composite components using magnetic particulate susceptors.

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